AD NUMBER
AD844592
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AD844592

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IN THE PRESENCE OF ABLATION

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18 SEPTEMBER 1968

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 68-163

BALANCE FOR MEASURING SKIN FRICTION
IN THE PRESENCE OF ABLATION

Prepared by:
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Donald B. Risher

ABSTRACT: This report describes a skin-friction balance that
is presently being used to measure shear stresses acting on the
wall of an ablative duct. Tests have been conducted in the
3 Megawatt Arc Tunnel with a Mach number of 3, a stagnation
enthalpy of 3000 BTU/lb, and a stagnation pressure of 20 atmos-
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The balance is a direct deflection measuring device in that
balance arm rotation is measured with a linear variable
differential transformer as the balance arm deflects due to
shear loads acting on the end of the balance arm.

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BALANCE FOR MEASURING SKIN FRICTION
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This report describes a skin-friction balance used to measure
shear stresses on an ablative wall in the U. S. Naval
Ordnance Laboratory's 3 Megawatt Arc Tunnel.

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Captain, USN
Commander

L. H. Schindel

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By direction

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ILLUSTRATIONS

BALANCE FOR MEASURING SKIN FRICTION
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1. INTRODUCTION

Currently at the Naval Ordnance Laboratory (NOL) there is much interest in a study of the interaction between ablation products and vehicle aerodynamics. Such studies have been carried out in the 3 Megawatt Arc Tunnel, since it is capable of producing the proper environmental conditions. In the present program, tests are being done in a Mach 3 flow at a stagnation enthalpy of about 3000 BTU/lb and supply gas pressures of 20 atmospheres. The test model is an axisymmetric duct made out of the ablation material. It can be instrumented for pressure, temperature, and skin-friction measurements. Figure 1 shows the duct, fabricated out of teflon, installed in the 3 Megawatt Arc Tunnel. The balance was designed at NOL to measure shear stresses up to 3.8 lb/ft² on an ablative wall with an ablative element of 0.417 inch in diameter. The balance is the first of its type designed and successfully used to measure shear stress on an ablative wall. It is significant that the balance successfully recorded transient data for the entire duration of the test.

2. LIST OF SYMBOLS

A	area of skin-friction element
b	flexure width
C	clearance between skin-friction element and duct wall
D	diameter of skin-friction element
E	modulus of elasticity (stainless steel $E = 28.5 \times 10^6$ psi)
I	moment of inertia of the beam
k	beam stiffness
L	moment arm length
ℓ	beam length

LIST OF SYMBOLS (Cont'd)

M_o moment acting on the beam

n   number of flexure

R   optical moment arms

S   deflection of light image

t   flexure thickness

T   torque

θ end slope of beam

ϕ rotation of balance arm

τ_{max} maximum shear stress

3. BALANCE DESCRIPTION

The skin-friction balance acts like a torsional moment arm to measure shear forces acting on the surface of a skin-friction element installed in an ablation duct. The skin-friction element is fastened to a balance arm; and when flow is exposed to the skin-friction element, the balance arm deflects by an amount proportional to the shear forces acting on the element. The skin-friction element is machined to match the contour of the duct and must fit flush with the duct surface so shear forces on the element will be similar to those on the smooth duct surface. Figure 2 shows the relationship between the skin-friction element and the ablation duct. The skin-friction element is allowed to deflect 0.015 inches before coming into contact with the duct wall, and it is important that the element move without interference over its intended operating range.

The balance arm pivots about a frictionless support known as the flexure (fig. 3). The flexure is sensitive to a torque applied to the arm perpendicular to the axis of the flexure shaft and rotation of the arm is proportional to the applied torque. Stiffness and thus sensitivity is a function of the design of the flexure. The flexure unit is designed to provide damping to the balance arm so as to eliminate periodic vibration of the arm.

Figure 4 illustrates the configuration of the balance arm.
The calibrating arm is located a distance of 1.941 inches down
from the pivot axis. Weights are hung from this arm at a
distance of two inches, and the resulting moment applied to the
flexure is equivalent to a torque applied at the surface of the
skin-friction element. Directly opposite the calibrating arm
is another shaft containing a transformer core. Movement of the
core is sensed by a linear variable differential transformer (LVDT).
The differential voltage produced is directly proportional to
the change in core position. This, of course, is an indication
of the amount of balance arm rotation. Since balance arm
rotation is proportional to the torque applied to the balance,
the voltage read out of the LVDT is a convenient indication of
forces acting on the surface of the skin-friction element.

4. BALANCE CALIBRATION

The skin-friction balance is calibrated by placing weights on
the calibrating arm and recording the voltage change of the LVDT
on an optical oscillograph. This voltage change is recorded as
a deflection of a high-intensity light beam on light sensitive
paper. A calibration curve, such as is shown in figure 8, is
drawn by plotting standard calibration weights versus deflection.
During the test run, the rotation of the balance arm, due to
shear forces acting on the skin-friction element, is recorded on
the optical oscillograph; and the resulting oscillograph deflections
can be related to a force acting on the calibrating arm with the
calibration curve. Then loads taken from the calibration curve
can be related to equivalent loads acting on the surface on the
skin-friction element by using the ratio of the lever arms.

5. BALANCE ASSEMBLY

Figure 5 shows the disassembled balance. The flexure unit is
shown in the figure installed in its position on the balance
arm. The flexure-balance arm assembly is supported by the
flexure holder also shown in the photograph. The flexure holder
is attached to the side of the balance housing, and provision is
made for vertical adjustment of the holder. This, of course, is
necessary to set the skin-friction element flush with the
surface of the duct.

The LVDT is attached to the balance housing and its location,
with respect to the transformer core, may be varied to provide
the proper clearance between the LVDT and the core. Access to the
calibrating arm is made by removing the cap from the pipe fitting

shown in the figure. Removal of this cap exposes the end of
the calibrating arm so that weights may be hung from the arm.

Figure 6 shows the balance installed in its receptacle in
the duct. The balance is threaded and sealed vacuum tight into
the duct, and a lock-nut arrangement is provided on the housing
so that it may be rotated after installation in the duct. This
provision is made so that the housing may be adjusted to align
the axis of the flexure perpendicular to the direction of air
flow in the duct.

6. DESCRIPTION OF THE FLEXURE

The flexure core is a one-piece unit consisting of an outer
ring with four flexures cantilevered from the ring and meeting
a shaft at the center of unit (fig. 3). The flexure core is
electrically machined from a single piece of stainless steel.
The unit is quite rigid for all motion of the shaft, with
respect to the outer ring, except rotation about the common axis;
and the rotational stiffness of the shaft is a function of the
bending stiffness of the flexures. The mode of bending of a
single flexure is analogous to the case of a beam with one end
fixed and the other end simply supported with a moment (M_o)
applied at the simply supported end (ref. (1)). The end
slope (θ) at simply supported end is given by:

$$\theta = \frac{1}{4} \frac{M_o \ell}{EI}$$

The stiffness of the beam is defined as:

$$k = M_o / \theta$$

$$k = M_o / \frac{1}{4} \frac{M_o \ell}{EI} = \frac{4EI}{\ell}$$

For the case of the four-flexure unit

$$k = n \frac{4EI}{\ell}$$

The moment of inertia of the beam is given by:

$$I = \frac{1}{12} bt^3 = \frac{1}{12} (0.100)(0.0068)^3 = 26.2 \times 10^{-9} \, in^4$$

The stiffness of the beam is:

$$k = n \frac{4EI}{\ell} = \frac{4 \times 4 \ (28.5 \times 10^6)(26.2 \times 10^{-30})}{0.300}$$

$$k = 3.982 \ \frac{in\text{-}lb}{rad}$$

The stiffness of the flexure was also measured experimentally, and the experimental values were found to be within 95 percent of the calculated values.

As was mentioned in the Introduction, the skin-friction balance measured transient data during the test run. The successful measurement of such data is attributed to the damping that was provided for the flexure unit. The damping system incorporated in the flexure unit was developed by Frank H. Durgin, Massachusetts Institute of Technology, Aerophysics Laboratory (ref. (2)). Figure 7 illustrates how damping is accomplished with the flexure. A damping wheel, attached to the flexure shaft, is sandwiched between two stationary disks. The gaps between the damping wheel and the stationary disks are filled with a damping fluid by evacuating the flexure area and allowing the damping fluid to flow into the chamber through the port shown in the figure. It was found that the ideal case would be a critically damped flexure-balance arm system; and, after some experimenting, a 0.5×10^6 cs. viscosity silicone fluid was shown to give the best results.

7. OPERATING RANGE OF THE BALANCE

In the design of the balance, there are a number of factors governing the maximum shear force that the balance is capable of measuring. Such factors as the clearance between the skin-friction element and the duct wall, the stiffness of the flexure, and the distance between the surface of the skin-friction element and the flexure shaft must be properly established to insure that the balance is capable of measuring the loads expected in the present test program. With the known flexure stiffness of 3.982 in-lb/rad, the operating limit of the balance was set by establishing the clearance between the skin-friction element and the duct wall and the length between the skin-friction element surface and the flexure shaft. Figure 2 shows that the skin-friction element was offset 0.005 inch from the center of the duct receptical to give the element a total travel of 0.015 inches. With the moment arm length set at 4.062 inch,

the maximum rotation of the balance arm (ϕ) is 0.00368 radian.
Since the resisting torque offered by the flexure is proportional
to the balance arm rotation by the stiffness of the flexure, the
torque at the maximum rotation angle is given by:

$$T = k\phi = (3.982)(0.00368)$$

$$T = 0.01465 \text{ in-lb}$$

The relationship between torque and maximum allowable shear
stress on the skin-friction element is:

$$T = \left(\tau_{s\,max}\right) A L$$

Where the area of the 0.417-inch diameter skin-friction element
(A) is $0.1365 in^2$:

$$\tau_{s\,max} = T/\, A\, L$$

$$\tau_{s\,max} = (0.01465)/(0.1365)(4.062)$$

$$\tau_{s\,max} = 0.0264 \text{ lb/in}^2 \text{ or } 3.801 \text{ lb/ft}^2$$

The maximum operating shear stress for the balance of 3.801 lb/ft²
is the maximum stress that may be imposed on the skin-friction
element before it comes into contact with the duct wall.

In future test programs, the balance may be subjected to
somewhat higher loads. Possibly, the most effective design
change on the balance, to increase its useful range, would be
to increase the flexure stiffness. An increase in web thickness
increases the moment of inertia of web by a factor of three.
Therefore, a slight increase in web thickness will give a
considerably stiffer flexure. A decrease in moment arm length (L)
would increase the limit of the balance since the flexure shaft
would be subjected to a greater maximum rotation. However,
decreases in moment arm length could subject the flexure to an
angle of rotation great enough to exceed the yield strength of
the flexure material.

8. DISCUSSION OF DATA

Calibration curves, prior to and after the hot test, were made.
These curves, with the curve used to reduce the data, are shown in
figure 8. In the data reduction, optical oscillograph deflection

every one-half second was noted for the 12-second run. For each deflection, a value of calibrated weight was found from the calibration curve, and from these values equivalent weights acting on the skin-friction element were calculated. From these equivalent forces, shear stress acting on the skin-friction element was found using the known area of the skin-friction element.

Figure 9 shows shear stress acting on the surface of the ablation element versus time. For the specific conditions of the test, the shear stress at the location of the balance, prior to the onset of ablation, was calculated to be 5.6 lb/ft^2 with a laminar boundary layer. Other data gained from the test show that ablation begins at approximately one second after the start of the test. The variation of skin friction with time is well predicted by a numerical procedure developed by Aerotherm Corporation, under NOL contract, in support of this program. The steady-state value that appears to be approached in the test program is within 10 percent of the predicted steady-state value.

9. CONCLUSIONS

The test proved to be very successful in measuring values of shear stress over the expected range. In the future, the balance will probably be modified to measure somewhat higher loads by modifying the flexure, as previously indicated. Also, the program will be continued by investigating different ablation materials. Materials of current interest for future tests are silica phenolic and graphite phenolic.

10. REFERENCES

(1) Roark, R. J., Formulas for Stress and Strain, McGraw-Hill Book Company, 1954.

(2) Durgin, F. H., "The Design and Preliminary Testing of a Direct Measuring Skin Friction Meter for Use in the Presence of Heat Transfer," Massachusetts Institute of Technology, Technical Report 93, June 1964.
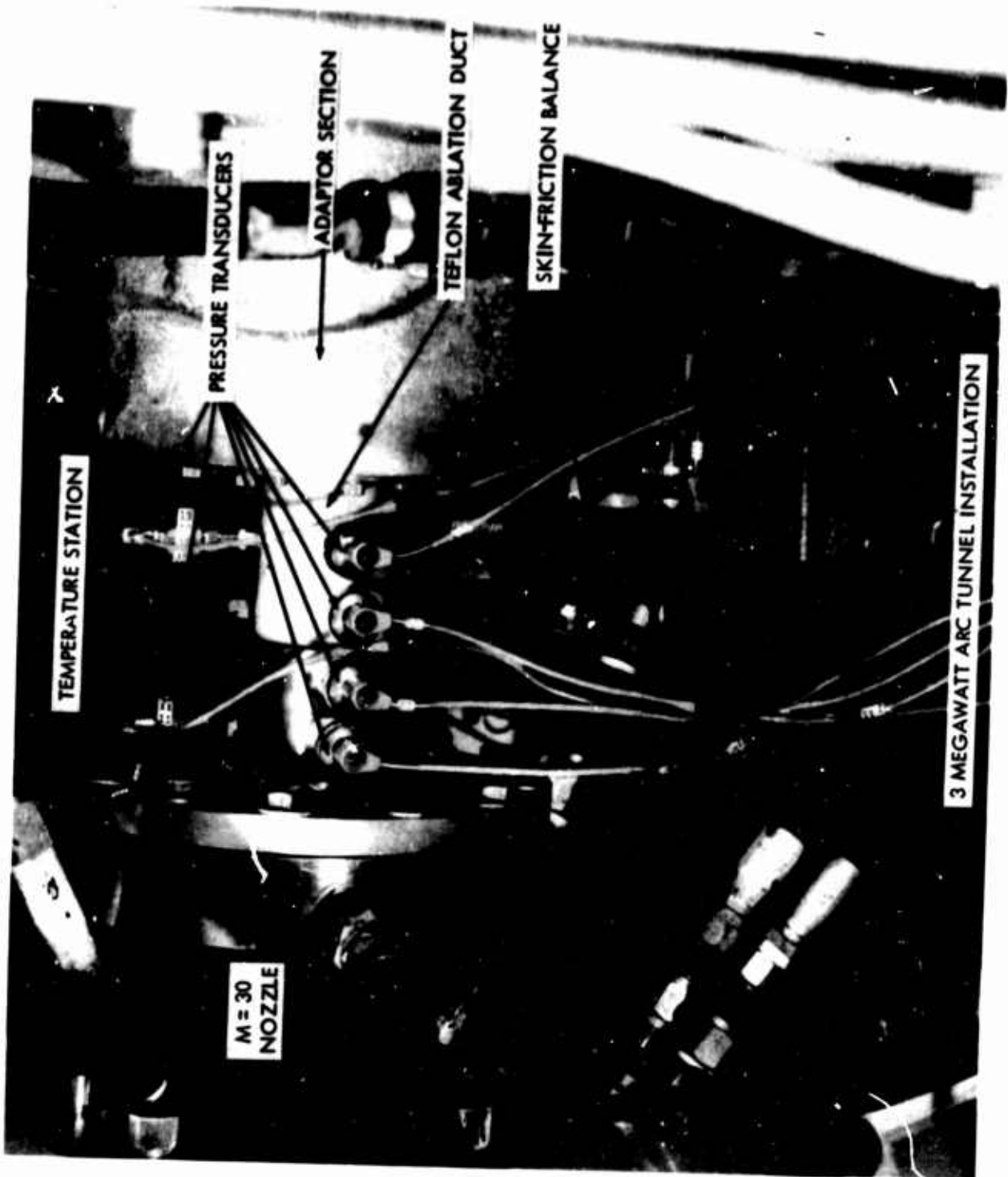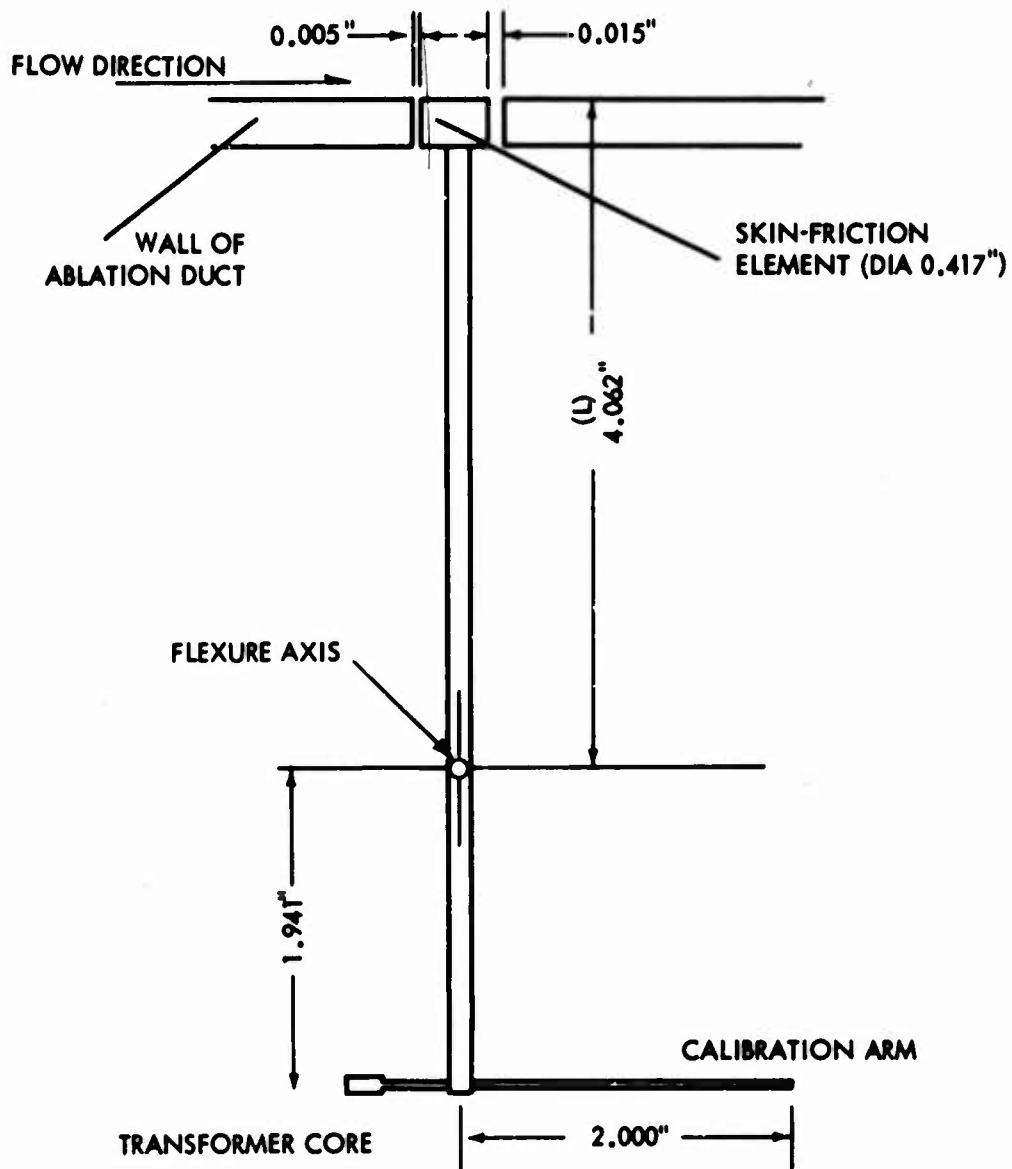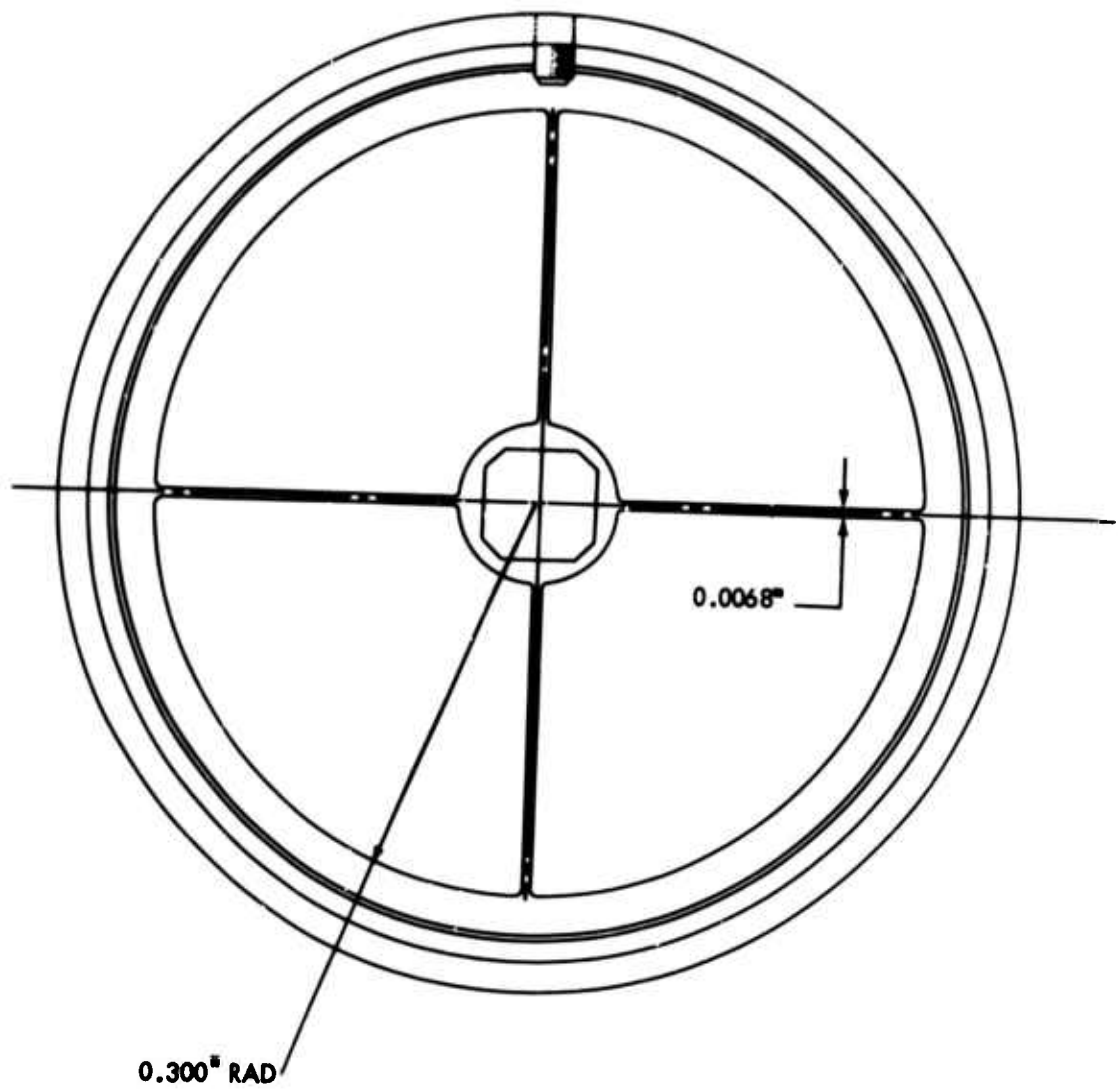
TEMPERATURE STATION

PRESSURE TRANSDUCERS

ADAPTOR SECTION

TEFLON ABLATION DUCT

SKIN-FRICTION BALANCE

M = 30 NOZZLE

3 MEGAWATT ARC TUNNEL INSTALLATION

FIG.1

BALANCE ARM SCHEMATIC

FIG. 2

0.0068"

0.300" RAD

FLEXURE CORE

FIG.3

FIG.4

SKIN-FRICTION BALANCE

FIG.5

TEFLON ABLATION
DUCT AND SKIN -
FRICTION BALANCE

FIG.6

FLEXURE COVER

FLEXURE COVER

FLEXURE CORE

DAMPER WHEEL

FLUID COVER

SHADED AREA TO BE FILLED
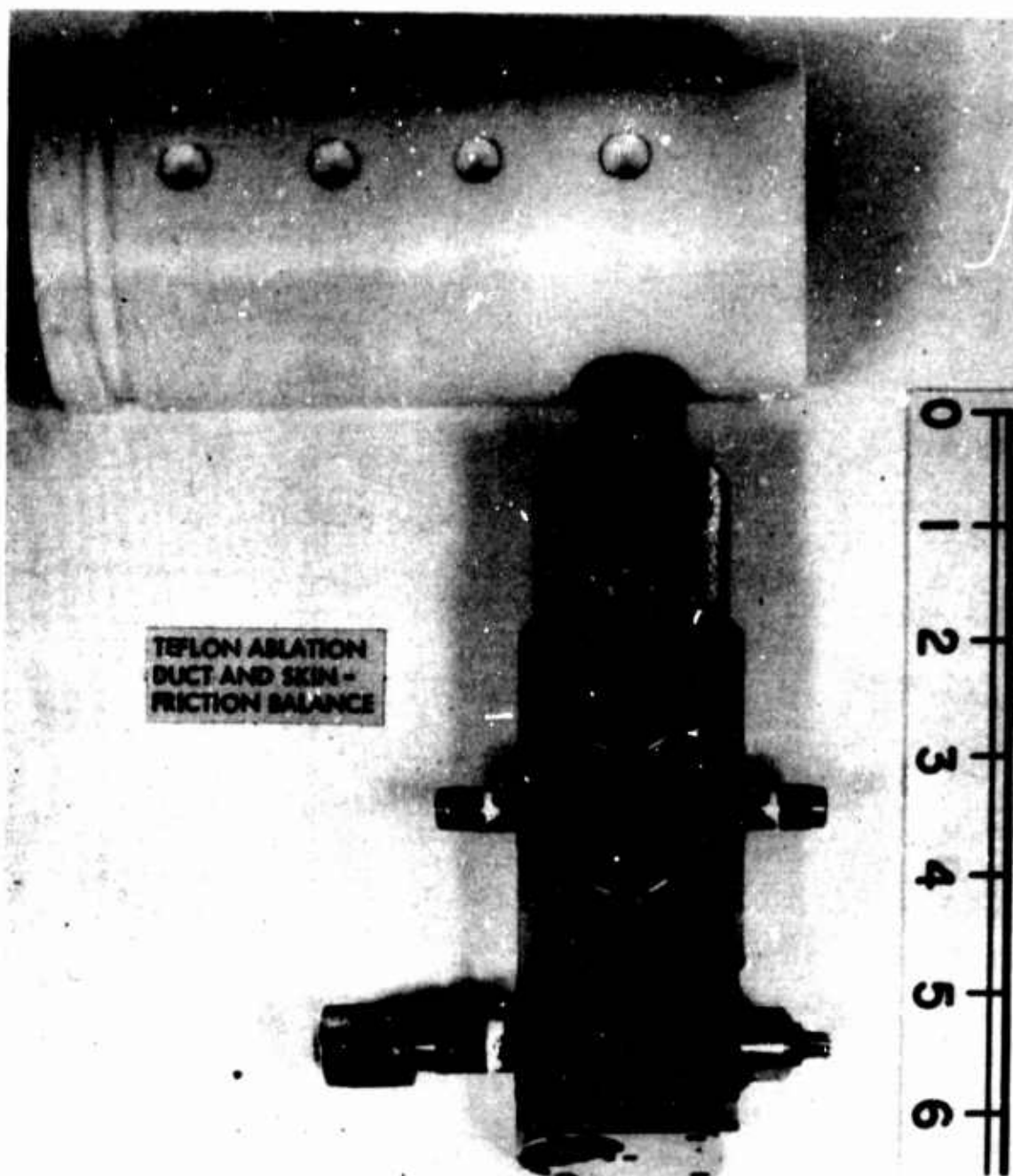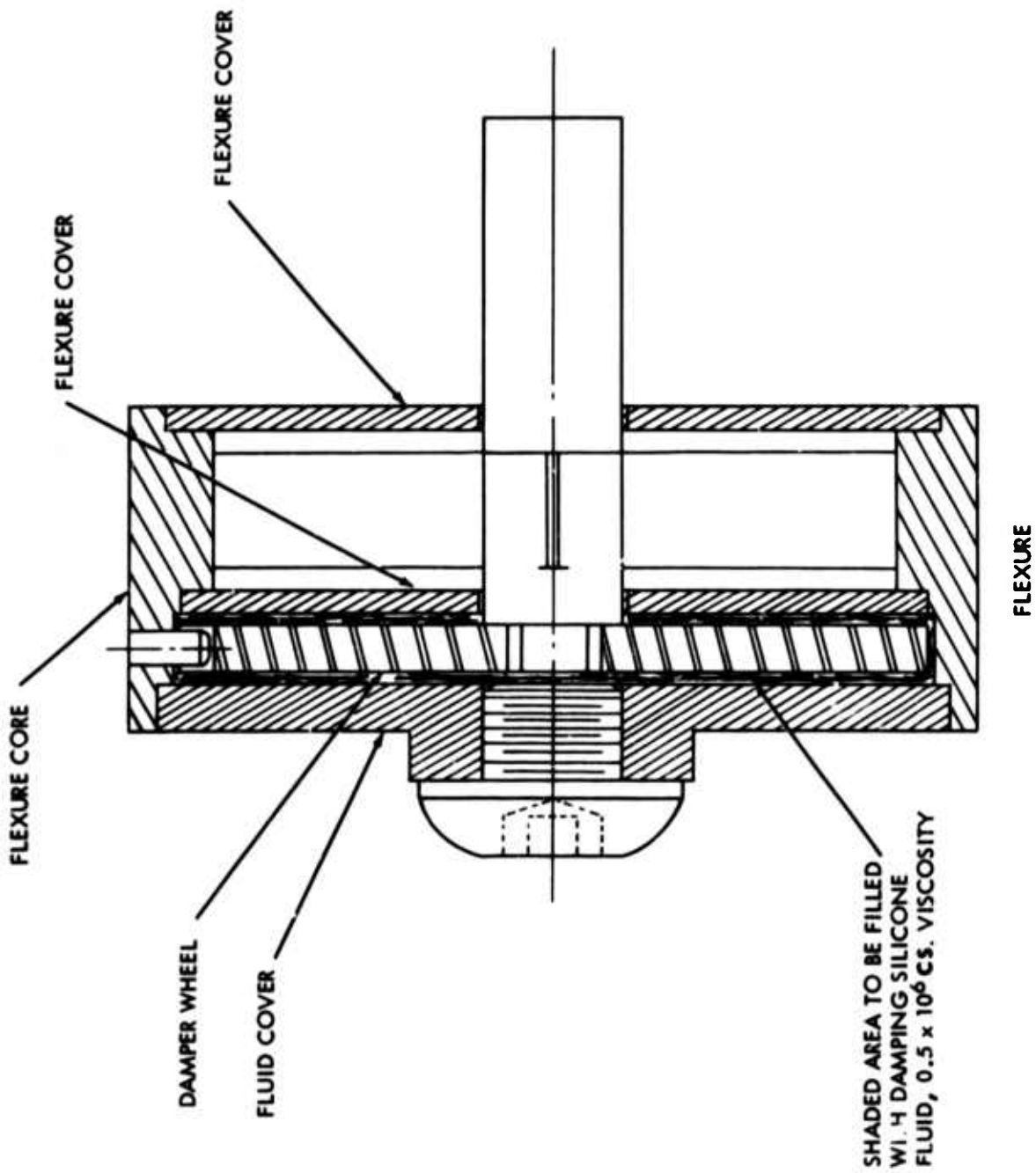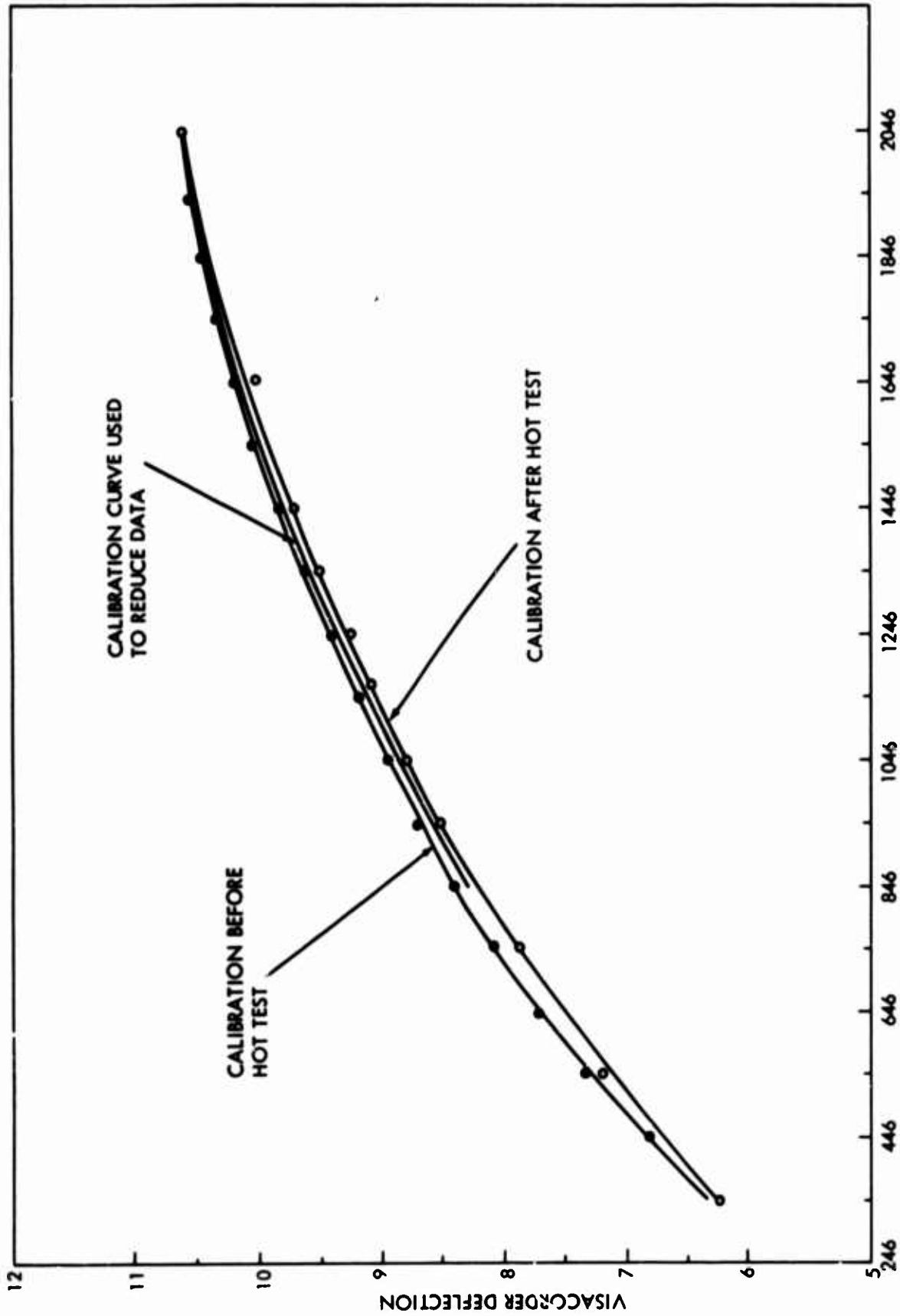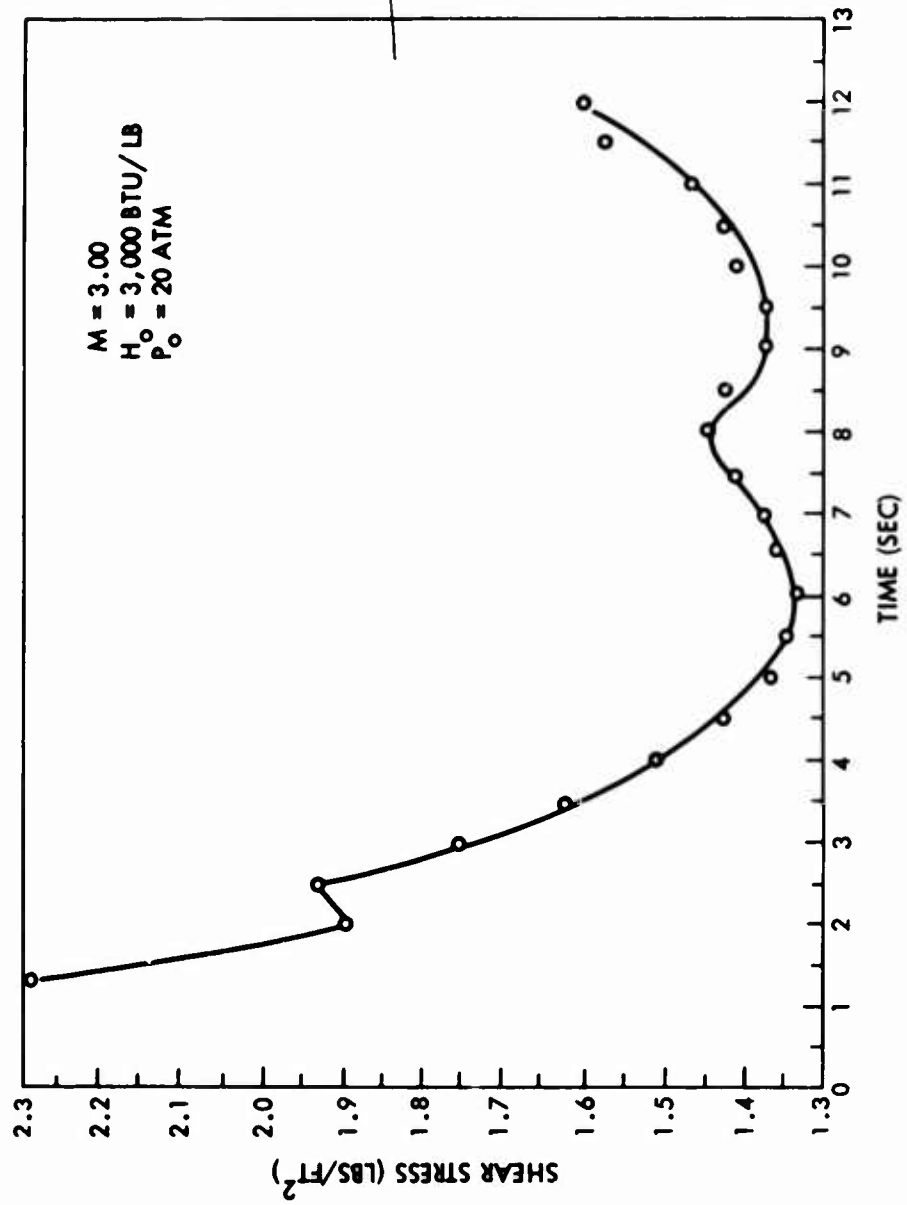WITH DAMPING SILICONE
FLUID, 0.5 x 10⁶ CS. VISCOSITY

FLEXURE
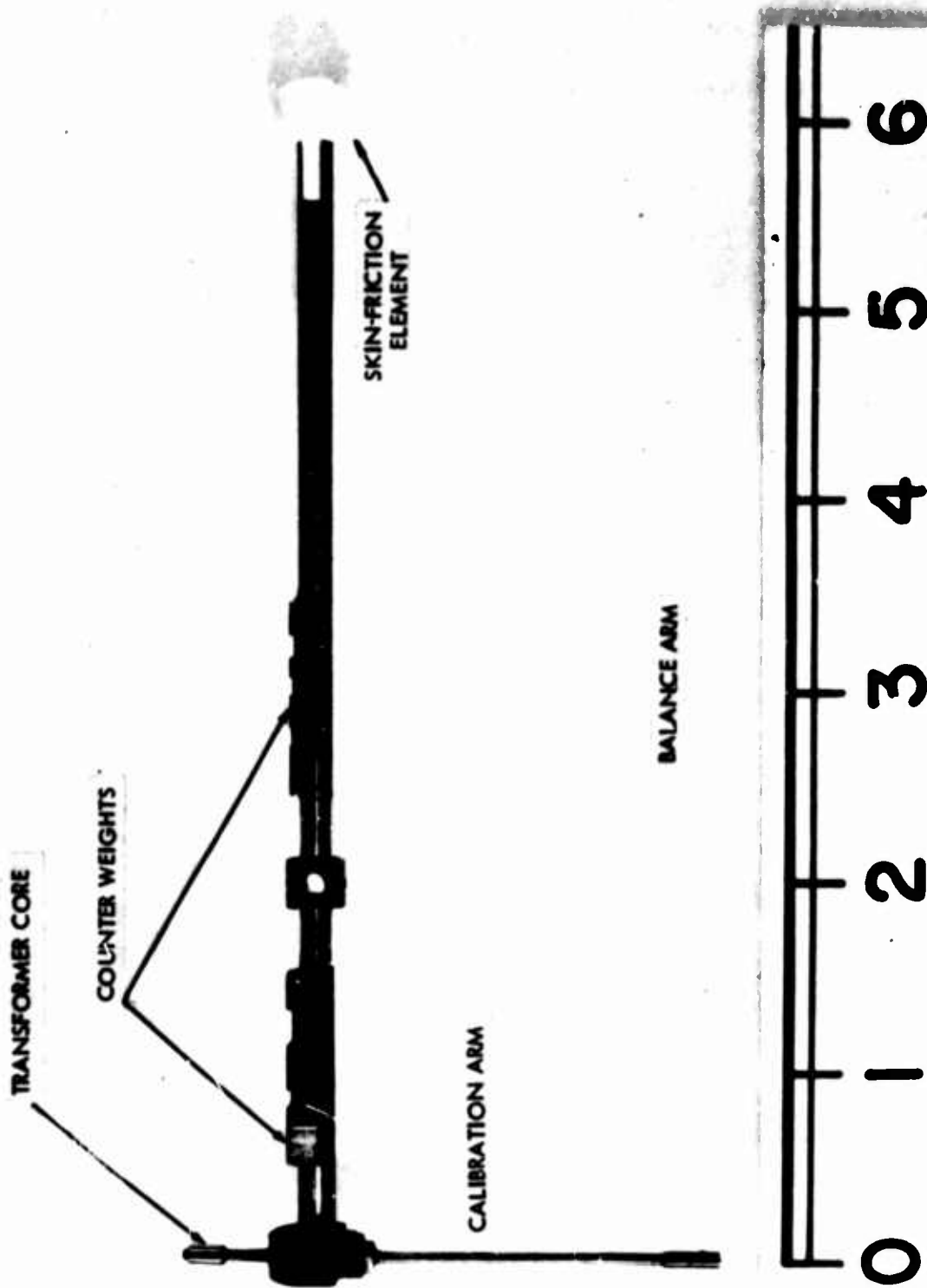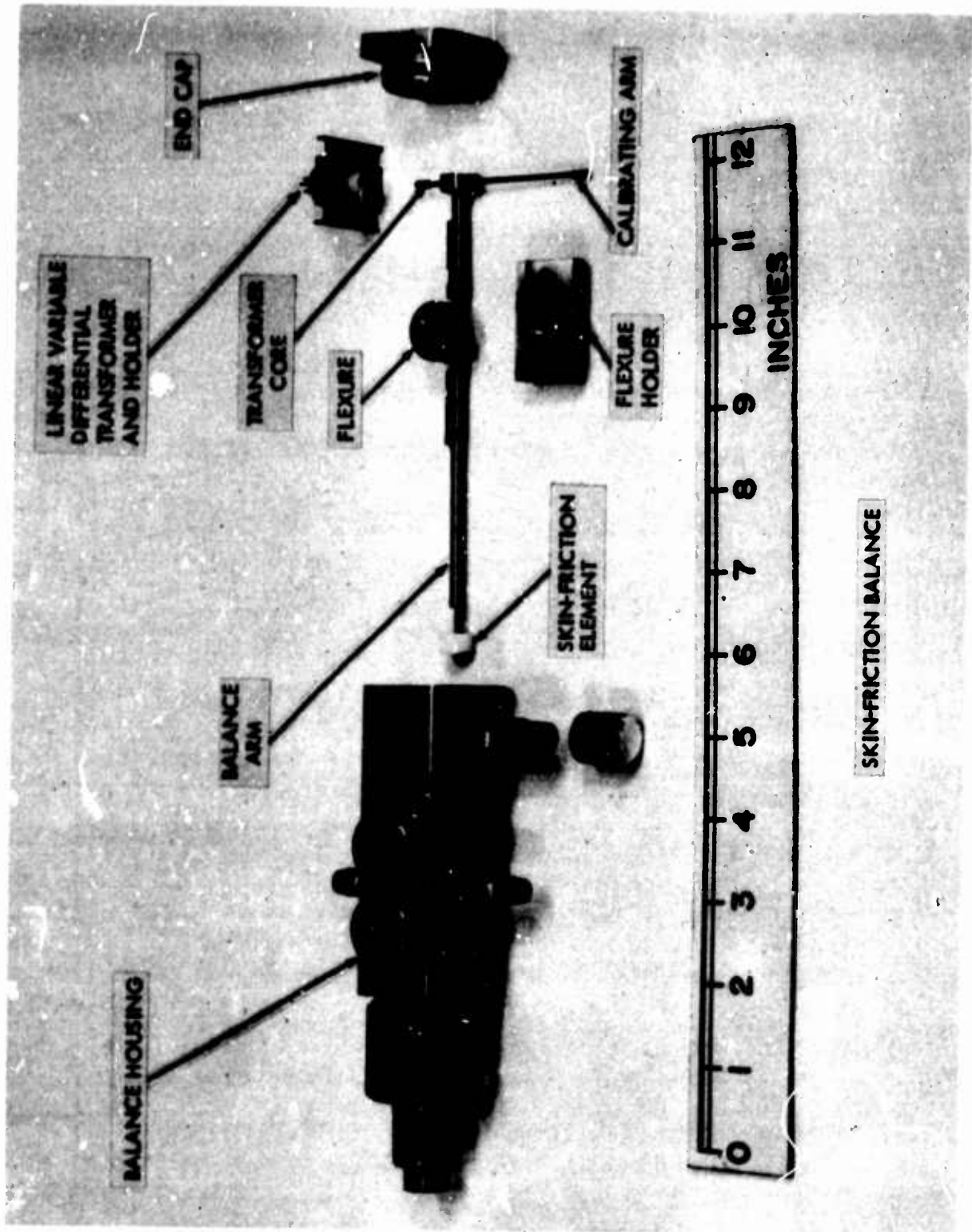
FIG.7

CALIBRATED WEIGHT
CALIBRATION CURVE
FIG. 8

DATA CURVE

FIG. 9

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
U. S. Naval Ordnance Laboratory White Oak, Maryland	Unclassified
	2b. GROUP

3 REPORT TITLE

Balance for Measuring Skin Friction in the Presence of Ablation

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final

5. AUTHOR(S) *(First name, middle initial, last name)*

James, R. Bruno, Donald B. Risher

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
18 September 1968	10	2
8a. CONTRACT OR GRANT NO	9a. ORIGINATOR'S REPORT NUMBER(S)	
b. PROJECT NO.	NOLTR 68-163	
c. MAT-03L-000-F008-9812	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	
d.		

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Skin Friction						
Flexure Core						
Ablation Duct						

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